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THESIS

MOBILE CUBESAT COMMAND AND CONTROL (MC3)

by

Robert C. Griffith

September 2011

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The Mobile CubeSat Command and Control (MC3) program will become the ground segment of the Colony II satellite program. The MC3 ground station contains Commercial Off-the-Shelf (COTS) hardware with Government Off-the-Shelf (GOTS) software making it an affordable option for government agencies and universities participating in the Colony II program. Further, the MC3 program provides educational opportunities to students and training to space professionals in satellite communications. This thesis analyzes the MC3 program from the program manager's point of view providing a Concept of Operations (CONOPS) of the program as well as initial analysis of MC3 ground station locations. Also included in this thesis is a future cost analysis of the MC3 program as well as lessons learned from the NPS acquisition process.

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MOBILE CUBESAT COMMAND AND CONTROL (MC3)

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requirements for the degree of

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ABSTRACT

The Mobile CubeSat Command and Control (MC3) program will become the ground segment of the Colony II satellite program. The MC3 ground station contains Commercial Off-the-Shelf (COTS) hardware with Government Off-the-Shelf (GOTS) software making it an affordable option for government agencies and universities participating in the Colony II program. Further, the MC3 program provides educational opportunities to students and training to space professionals in satellite communications. This thesis analyzes the MC3 program from the program manager's point of view providing a Concept of Operations (CONOPS) of the program as well as initial analysis of MC3 ground station locations. Also included in this thesis is a future cost analysis of the MC3 program as well as lessons learned from the NPS acquisition process.

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LIST OF ACRONYMS AND ABBREVIATIONS

AFSCN	Air Force Satellite Control Network
AS&T	Advanced Systems & Technology
BP	Blossom Point
C2	Command and Control
CGA	Common Ground Architecture
COMET	Common Environment for Testing
COTS	Commercial Off-the-Shelf
DSN	NASA Deep Space Network
EL-CID	Equipment Location Certification Information Database
GENSO	Global Educational Network for Satellite Operations
GOTS	Government Off-The-Shelf
GSS	Ground Station Server
ISS	International Space Station
KFS	Kuali Financial System
LEO	Low Earth Orbit
LLNL	Lawrence Livermore National Laboratory
MCC	Mission Control Client
MC3	Mobile CubeSat Command and Control
NPS	Naval Postgraduate School
NPSCuL	NPS CubeSat Launcher
NRL	Naval Research Laboratory
NRO	National Reconnaissance Office
NTIA	National Telecommunications & Information Administration
OUTSat	Operationally Unique Technology Satellite
P-POD	Poly Picosatellite Orbital Deployer
PI	Principal Investigator
R&D	Research and Development
RFI	Request for Information
RTS	Remote Tracking Station
SGLS	Space Ground Link System

SGSS	Space Ground System Solutions
SPFA	Sponsored Program Financial Analyst
STARE	Space-based Telescope for the Active Refinement of Ephemeris
STK	Satellite Took Kit
TNC	Terminal Node Controller
TT&C	Telemetry, Tracking, and Command
VPN	Virtual Private Network

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I. HISTORY OF SATELLITE GROUND STATION NETWORKS

Satellite programs have grown considerably since their onset at the beginning of the space race in the 1950s. In the beginning, each satellite program was unique and there were few similar Command and Control (C2) architectures. As most of these early satellites were placed in Low Earth Orbit (LEO), the time available for the satellite to establish a communications link with the ground was limited. In order to better pass C2 and payload data more ground stations were needed and were subsequently placed at strategic points around the world to optimize coverage and allow more access time to download data. As a result the idea of establishing a network of ground stations arose as well as the standardization of communication frequencies [1].

A. NASA DEEP SPACE NETWORK

The NASA Deep Space Network (DSN) was established in 1958 to provide communications to deep space autonomous spacecraft, alleviating the need for separate communications systems. The network has assisted the space community in various programs and currently operates three ground stations in the United States, Spain, and Australia. These stations are strategically placed 120 degrees apart allowing for continuous deep space observation. Due to the deep space communications links needed each complex has varying sizes of antennas with the biggest being 70 meters. Each complex controls its own antennas and then sends the information back to the Jet Propulsion Laboratory to be processed. The DSN enables NASA to track spacecraft position and velocity, send C2 commands, and gather satellite payload data [2]. Figure 1 shows the DSN locations throughout the world and antenna sizes each operates.

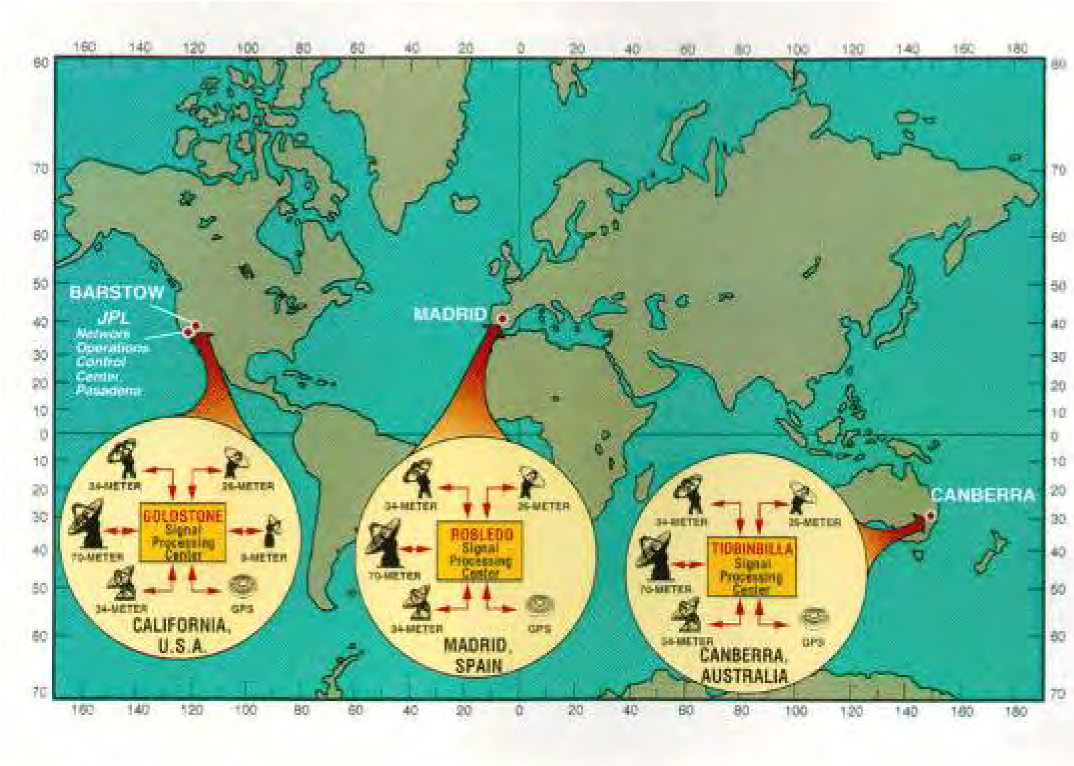

Figure 1. NASA DSN as of 1992 (From [2])

B. AIR FORCE SATELLITE CONTROL NETWORK

The Air Force Satellite Control Network (AFSCN) was initially created in 1959 to support early Intelligence Community and Department of Defense spacecraft. The AFSCN was constructed to transmit C2 commands to orbiting spacecraft utilizing ground stations throughout the world. Unlike NASA's DSN, the AFSCN would be able to send commands to other ground stations via a primary node. The first C2 primary node was located in Palo Alto, California, but was later moved to Sunnyvale, California as operations increased. Today the Sunnyvale location is the backup to the Primary Operating Node located at Schriever Air Force Base near Colorado Springs, Colorado. C2 command requests are generated by the satellite's respective space operations centers and

sent to the primary operating node. The C2 data is then scheduled and transmitted to the respective Remote Tracking Stations (RTS) based on availability and location of the satellite.

As the number of missions and spacecraft increased so did the number of ground stations accompanied by advances in technology. At the onset, each satellite operated at different C2 frequencies, but later the Space Ground Link System (SGLS) frequencies became the standard for C2 data. SGLS today operates in the upper S and L communications bands; 1755-1850 megahertz uplink and 2200-2300 megahertz downlink. Currently, the AFSCN operates under Air Force Space Command and the 50th Space Wing headquartered at Schriever Air Force Base. They are also the primary C2 node and control eight remote tracking stations (RTS) located in Hawaii, California, Colorado, New Hampshire, Greenland, England, Diego Garcia, and Guam. These remote locations are interconnected and pass on Telemetry Tracking and Command (TT&C) and mission data to a wide variety of satellites in different orbital regimes [3]. Figure 2 depicts these eight locations throughout the world.

Figure 2. AFSCN Locations (From [2])

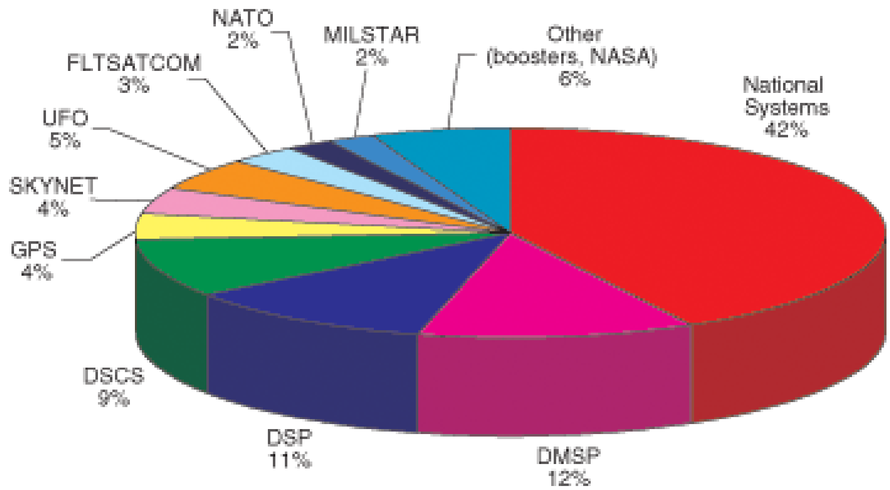

Figure 3. AFSCN usage (From [3])

Figure 3 demonstrates the many systems that the AFSCN supports. One drawback to the AFSCN are the numerous satellites requesting access compared to the number of operating ground stations which may result in long lag times in C2 commands to the spacecraft. While the AFSCN does collect some mission data from spacecraft, they do not provide the bulk of payload data downlink for every government program as other ground stations, such as Buckley Air Force Base which provides this capability for government systems [4]. Overall the AFSCN has been an effective network in handling data across various programs.

C. GLOBAL EDUCATIONAL NETWORK FOR SATELLITE OPERATIONS (GENSO)

As small satellites have grown in popularity and functionality so has the need grown to create an integrated ground station network serving these satellites. Most small satellites operate in LEO and do not last as long as those satellites at higher altitudes. In addition, small satellites do not have as much power as larger satellites making the communications link to the ground much more difficult. As more universities and organizations invest time and money into small satellites a ground station network that could pass C2 and payload data across a distributed network, much like the AFSCN, would be highly beneficial.

The Global Educational Network for Satellite Operations (GENSO) project is designed to be an Amateur radio and university ground station network that would enable users to pass their C2 data to different locations throughout the world via the Internet. The GENSO project is sponsored by the European Space Agency and is contracted through Vega Space along with help from universities throughout the world and amateur satellite radio teams [5].

Standard software and hardware elements are required in order to participate in this network. The Ground Station Server (GSS) and the Mission Control Client (MCC) are the two software programs needed to store and retrieve data from satellites across the network. These programs run locally on a university's computer and communicate via the Internet with the primary node located at the University of Vigo in Spain. The primary node runs an authentication server that validates the user on the network. The GSS stores data from a satellite pass and then allows the respective satellite's owner to retrieve data via the primary node through the authentication server. After authentication, the GSS notifies the satellite's home MCC and data is transferred to the home ground station. Also, through the GSS and MCC, a satellite's owner may use another GENSO ground station to communicate, upload commands and retrieve data, with their spacecraft. The MCC software enables all ground stations to track all compatible spacecraft on the network. The hardware requirements are the standard YAESU rotor, an ICOM radio, and a Terminal Node Controller (TNC). Currently, GENSO has released its first software version and is conducting system testing with its second [5].

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II. MOBILE CUBESAT COMMAND AND CONTROL (MC3)

The MC3 program initially is a joint Naval Research Laboratory (NRL) and Naval Postgraduate School (NPS) project that, in addition to creating a ground station network for CubeSats, also creates educational and scientific learning opportunities for university students and military officers studying at NPS and other universities.

A. MC3 OVERVIEW

1. Colony Program

The National Reconnaissance Office (NRO) has, over the past couple of years, invested in CubeSats through the Colony Program. The Colony Program's objectives are to conduct Advanced Systems & Technology (AS&T) Research & Development (R&D) experiments using CubeSats in order to mature technology in space at a lower cost. The Colony Program also creates educational opportunities at universities and motivates spacecraft engineering development throughout industry. The NRO initially contracted the Colony I bus through Pumpkin Incorporated and has contracted for the Colony II bus through Boeing. These contracts have different bus requirements, but enable universities or other government entities to create their own payload and integrate with the bus [6, 7]. The actual Colony I bus is depicted in Figure 4, while the Colony II bus is depicted in Figure 5.

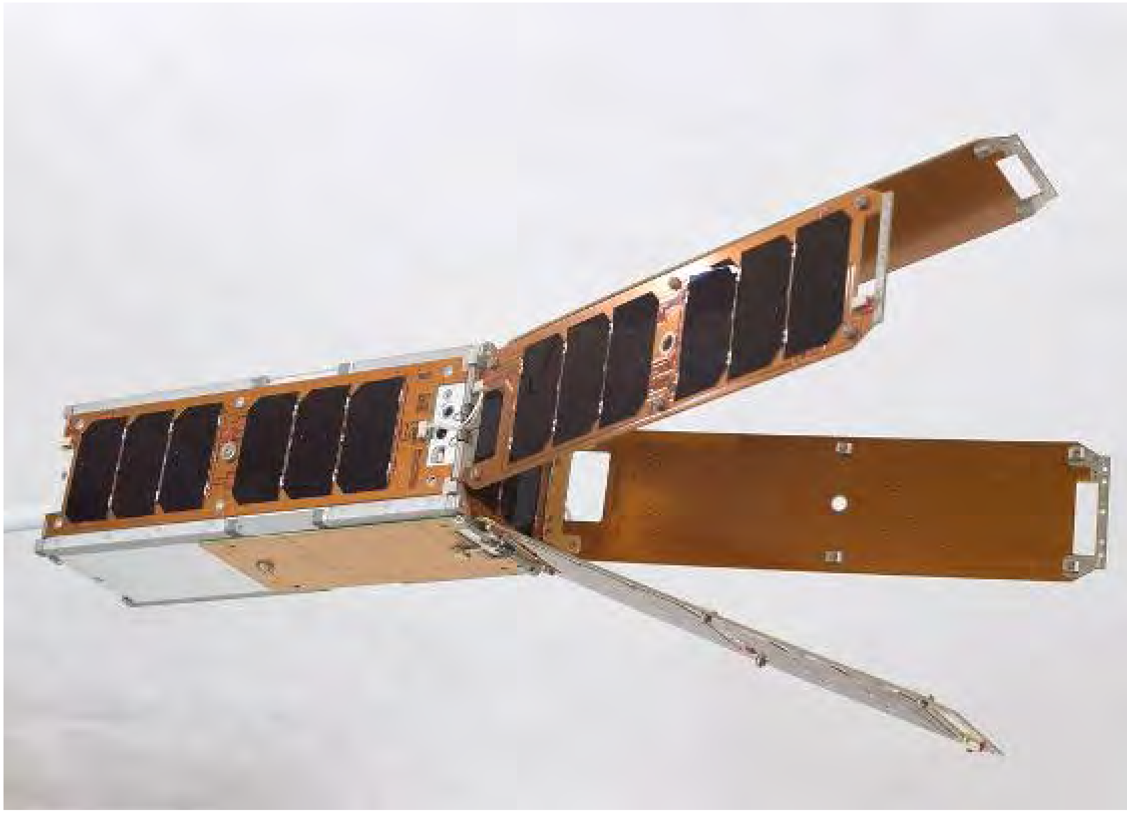


Figure 4. Colony I Bus (From [6])

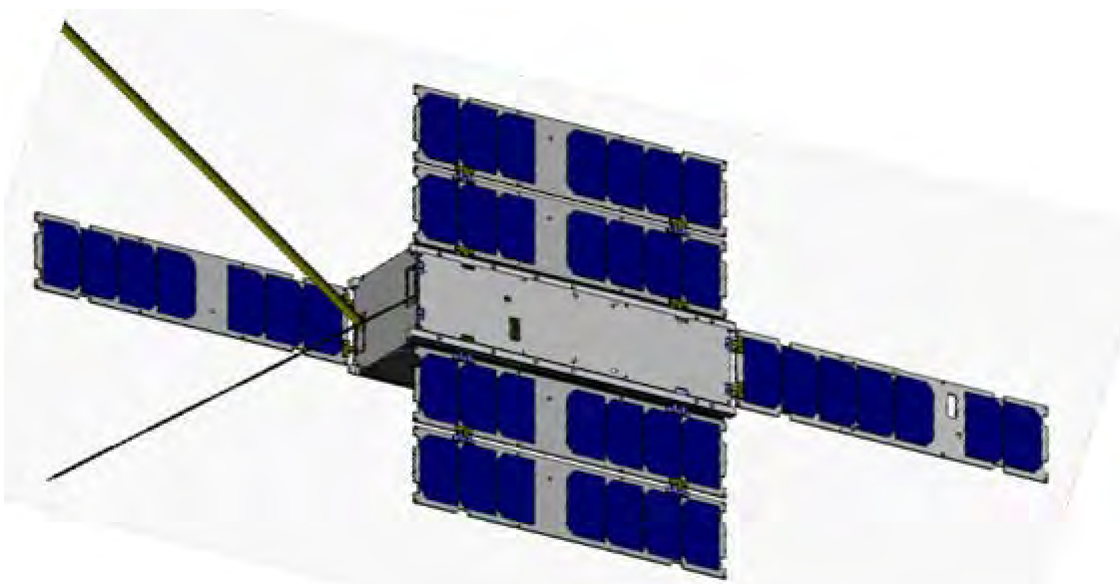


Figure 5. Colony II Bus (From [7])

2. MC3 Specifications

The MC3 program is the ground architecture for Colony II spacecraft. Due to the expected orbits and power restrictions of the spacecraft an integrated ground station architecture was required in order to maximize data download and command upload. NRL was tasked to develop and construct three MC3 ground stations to be compatible with Colony II spacecraft. During this process NRL would also produce a MC3 parts list and build instructions so that NPS could purchase the parts and construct a fourth MC3 to be permanently based at NPS. NPS would assist in validating the assembly and operations manuals that the NRL developed. NRL designed the MC3 with four antennas designed for operating at the UHF and S-Band frequencies with all other associated antenna hardware operated by a single laptop computer. The hardware used is Commercial Off-the-Shelf (COTS) with the software running the ground station being Government Off-the-Shelf (GOTS).

The 450 MHz antenna pictured in Figure 6 is the actual antenna shipped to NPS by NRL in conjunction with the MC3 project. Individual elements were put together by students and the antenna is awaiting installation.

Figure 6. 450 MHz Antenna

Figure 7 is a picture of the 915 MHz antenna as purchased and delivered to NPS.

Figure 7. 915 MHz antenna

Figure 8 is a picture of the two 2.1 GHz antennas.

Figure 8. 2.1 GHz Antenna

Figure 9 is a picture of the four 2.2 GHz antennas as assembled at NPS.

Figure 9. 2.2 GHz Antenna

Figure 10 is the current MC3 rack with parts procured by NPS. Not all parts required for the MC3 are depicted as some are still on order or awaiting arrival from NRL.

Figure 10. MC3 Rack

3. Common Ground Architecture (CGA)

CGA software has been in existence since 1982 and has provided functionality to a wide degree of satellite programs. The Harris Corporation developed the pre-cursor to CGA, called the Common Environment for Testing (COMET). However, after some employees split with Harris, a new company formed called Space Ground System Solutions (SGSS), which carried on the

work at the Blossom Point (BP) Tracking Facility to support NRL space missions utilizing their own version of COMET named CGA. CGA is open architecture software that enables coding for any aspect of a spacecraft mission from testing to on orbit operations. Also through CGA an entire ground station can be automated to track and communicate with satellites. The NRL BP Tracking Facility takes advantage of this and maintains an unmanned watch floor for all the satellite programs that it tracks. The user can input schedules into the CGA software and the software automatically assigns resources (e.g. antennas) to track and pass commands and data when the satellite is overhead. A study on the cost savings potential of this autonomous capability could be a thesis in itself when compared to other satellite operations centers and their 24 hour manned watch floors. CGA also enables scheduling through remote locations utilizing resources via a network. Figure 11 shows the functionality of CGA [8].

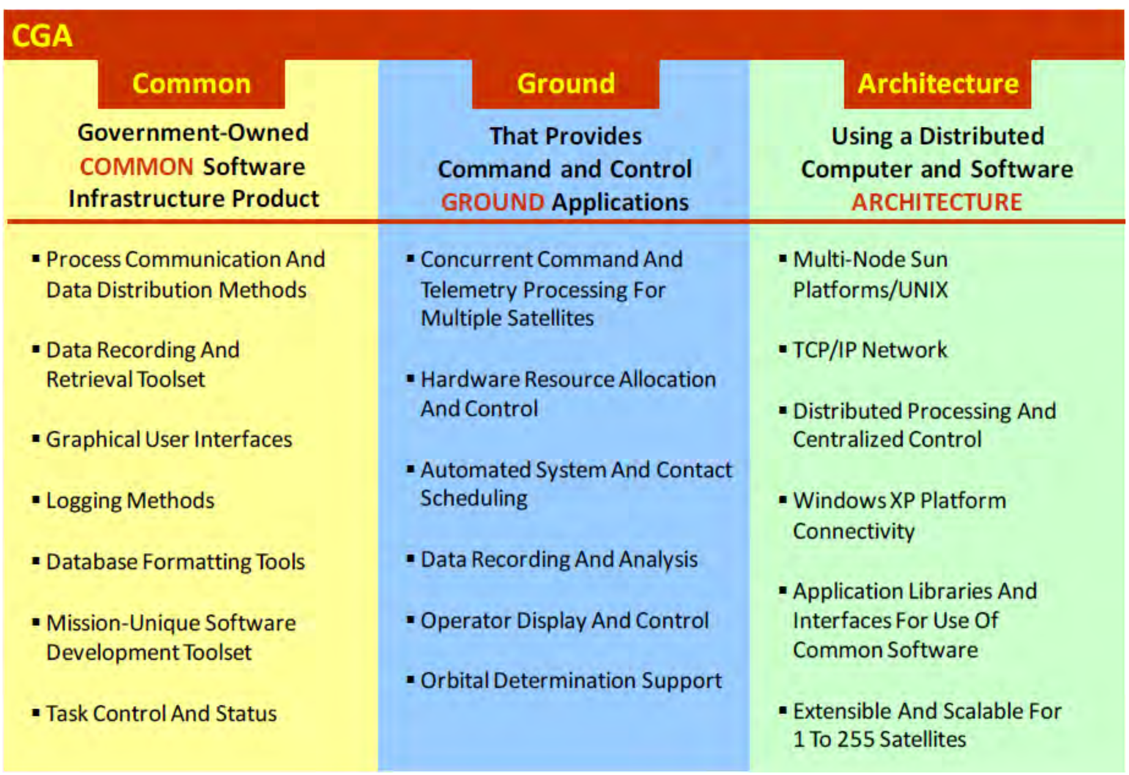


Figure 11. CGA Capabilities and Characteristics (From [9])

B. CONCEPT OF OPERATIONS

The MC3 ground stations will be deployed at select universities and locations throughout the world and will be connected through a Virtual Private Network (VPN) via the Internet. The MC3 that will be stationed at NPS will be the primary scheduling authority for the network. Possible locations/nodes for the MC3s include: Logan, UT; Fairbanks, AL; Guam; College Station, TX; Dayton, OH; Albuquerque, NM; University of Hawaii; and Melbourne, FL.

Figure 12 demonstrates the desired network configuration with all MC3s connected via VPN over the Internet. The MC3s will send and receive TT&C data for both the bus and payload as well as receive payload data from Colony II spacecraft. Much like GENSO and the AFSCN, the satellite's owner can input a request into the system for the type of command desired and the NPS CGA node will schedule the event via the CGA software. CGA will then determine which MC3 is available to communicate with the spacecraft based on time, location, priority, and MC3 availability. The command will then be communicated to the spacecraft and data will be received and transmitted back to the satellite's owner via the VPN. CGA's open architecture and the overall networking capacity allows for significant growth to support various space missions.

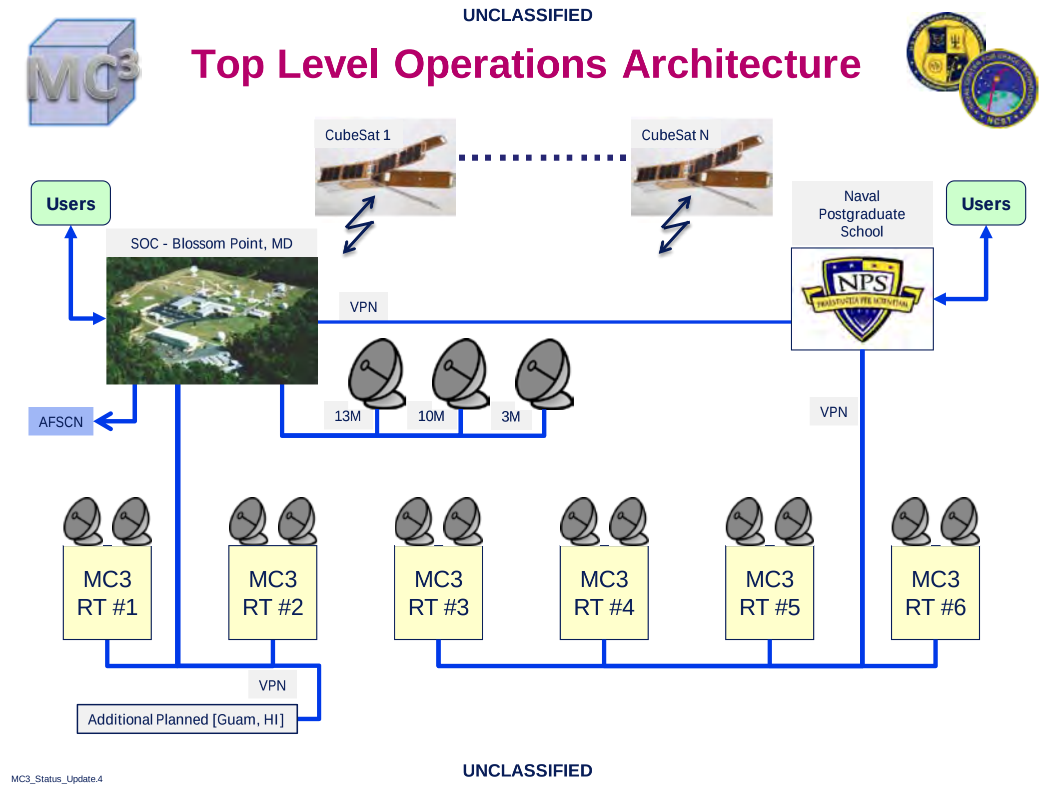


Figure 12. MC3 Architecture (From [9])

C. GROUND STATION LICENSING

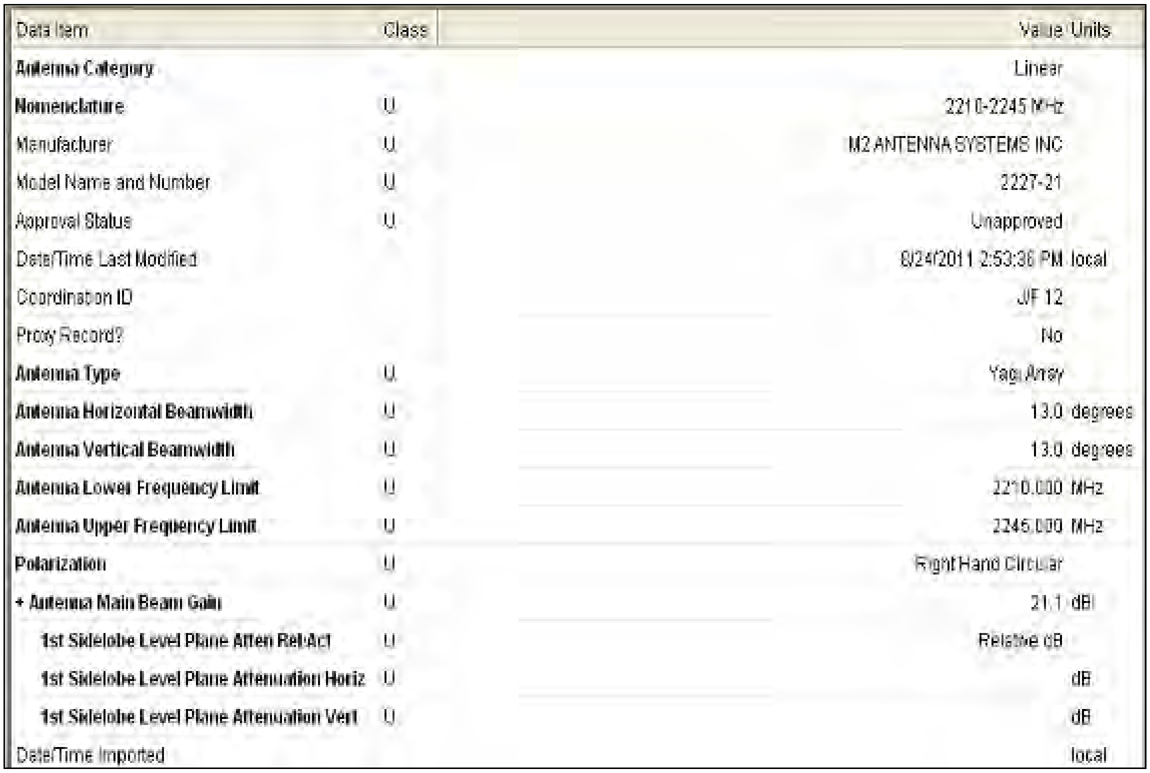
A ground station must request authorization before transmitting on certain frequencies from the National Telecommunications & Information Administration (NTIA). The Equipment Location – Certification Information Database (EL-CID) computer program aids in accomplishing the authorization process. Upon completion of data entry for equipment parameters in the program, the certification application can be emailed to the NTIA for approval. Amateur radio frequencies transmitted by ground stations are exempt from this process if there are amateur radio licensed individuals operating the ground station; but they must register with the amateur radio community. All other transmitted frequencies must obtain approval from the NTIA before transmitting.

The ground station certification process begins with inputting select parameters of the ground station into the EL-CID program. The NTIA requires a list of all radio receivers and transmitters operating at the ground station as well as a list of antennas. Table 1 lists the MC3 radios and antennas input into EL-CID:

Nomenclature	**Purpose**
ICOM 9100 radio (2)	Transceiver
GDP radio	Receiver
Yagi Antenna	450 MHz antenna
917 Yagi Antenna	915 MHz antenna
1975-23 Yagi Antenna	1925-2100 MHz antenna
2227-21 Yagi Antenna	2210-2245 MHz antenna

Table 1. MC3 Radios and Antenna

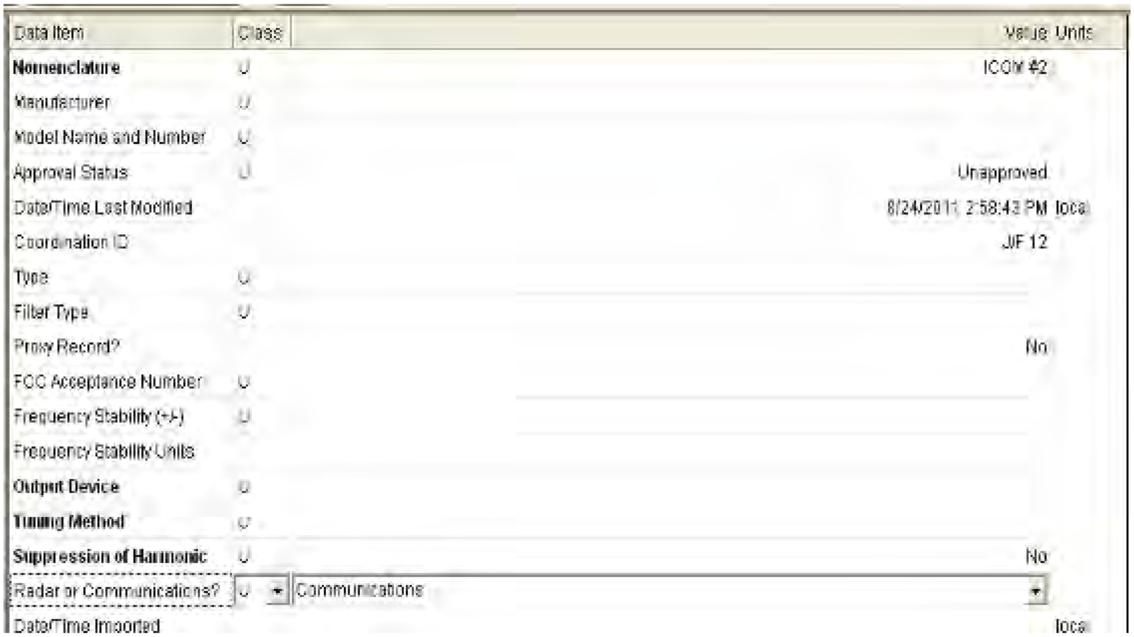
EL-CID requires specific parameters of each radio and antenna listed. Figure 13 displays the information requested from the EL-CID program for an antenna:



Data Item	Class	Value	Units
Antenna Category		Linear	
Nomenclature	U	2210-2245 MHz	
Manufacturer	U	M2 ANTENNA SYSTEMS INC	
Model Name and Number	U	2227-21	
Approval Status	U	Unapproved	
Date/Time Last Modified		8/24/2011 2:53:36 PM	local
Coordination ID		JF 12	
Proxy Record?		No	
Antenna Type	U	Yagi Array	
Antenna Horizontal Beamwidth	U	13.0	degrees
Antenna Vertical Beamwidth	U	13.0	degrees
Antenna Lower Frequency Limit	U	2210.000	MHz
Antenna Upper Frequency Limit	U	2245.000	MHz
Polarization	U	Right Hand Circular	
+ Antenna Main Beam Gain	U	21.1	dBi
1st Sidelobe Level Plane Atten Rel/Act	U	Relative dB	
1st Sidelobe Level Plane Attenuation Horiz	U		dB
1st Sidelobe Level Plane Attenuation Vert	U		dB
Date/Time Imported			local

Figure 13. EL-CID screenshot for Antenna

The information compiled for each antenna is listed in Table 1; however, some of the parameters were unknown and a Request for Information (RFI) was submitted to the manufacturer. Some of the information for the radios listed in Table 1 is still needed from the manufacturers. Figure 14 shows the information required for one of the radios at NPS:



Data Item	Class	Value	Units
Nomenclature	U	ICOM #2	
Manufacturer	U		
Model Name and Number	U		
Approval Status	U	Unapproved	
Date/Time Last Modified		8/24/2011 2:58:43 PM	local
Coordination ID		J/F 12	
Type	U		
Filter Type	U		
Proxy Record?		No	
FCC Acceptance Number	U		
Frequency Stability (+/-)	U		
Frequency Stability Units			
Output Device	U		
Timing Method	U		
Suppression of Harmonic	U	No	
Radar or Communications?	U	Communications	
Date/Time Imported			local

Figure 14. EL-CID screenshot for radio

At the time of this writing, the certification form for the NPS ground station is not complete; but once the missing information is obtained the form will be emailed to the NTIA for approval.

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III. MC3 PROGRAM MANAGEMENT

The Program Manager aspect of this thesis offered opportunities to learn about the acquisition process at NPS. As Program Manager, the author's responsibilities included the overall MC3 budget, MC3 parts acquisition, and the coordination of MC3 handover from the NRL to NPS. A wealth of knowledge was gained by being the first program manager of the MC3 project.

A. BUDGET

The fiscal year 2010 budget consisted of funds received to cover the MC3 project from July 2010 through August 1, 2011; however, an extension was requested from the sponsor to extend the funds through September 30, 2011. Estimates of the amounts needed were allotted to each standard category to track the costs. Table 2 lists the categories and associated estimated obligations as of August 14, 2011:

Fund Category	Estimated Obligations (nearest $100)
Labor	$29,000
Travel	$5200
Equipment/Supplies	$108,500
Contract/Services	$3,000
Indirect	$29,000
Total	$174,700

Table 2. Estimated Funding as of 14 August 2011

Figure 15 is a pie chart delineating the percentage of budget expenses of the MC3 program. The initial allocation of funds was more heavily distributed towards travel and labor, but as the project progressed, the need for travel dwindled and the amount of equipment to be purchased increased so more funds were allocated towards equipment.

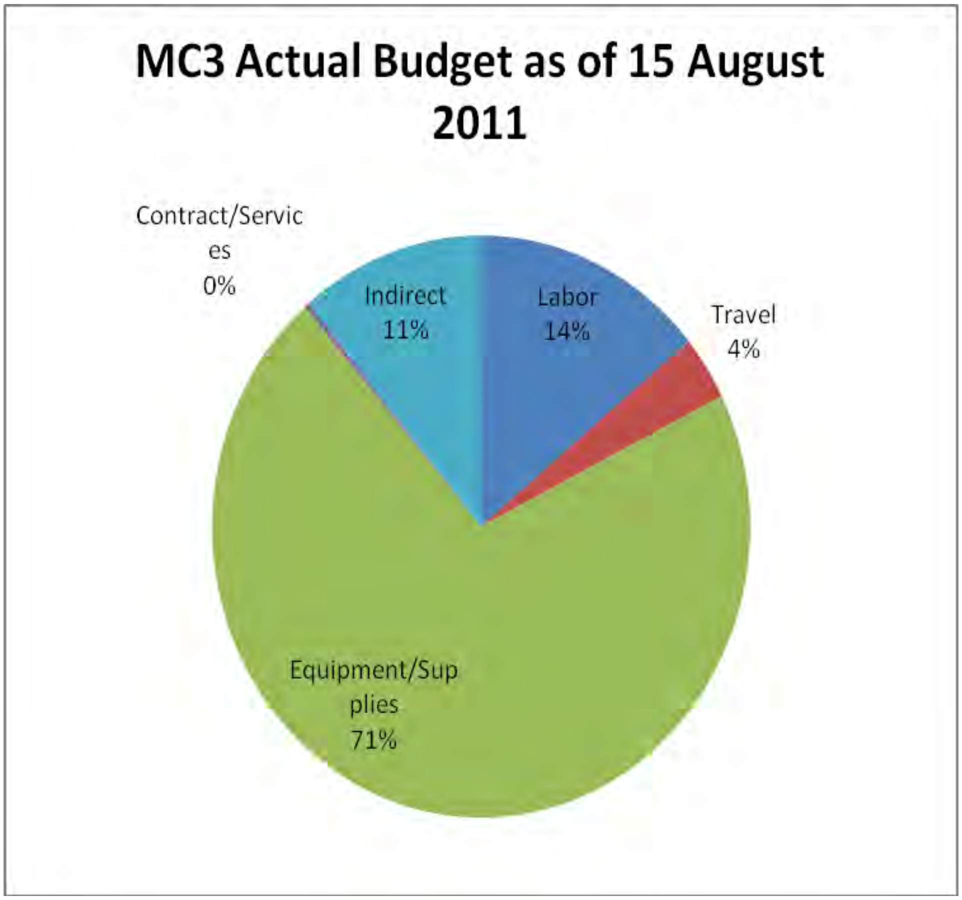

Figure 15. Actual MC3 Budget Allocation

1. Labor

Labor funds for the MC3 project were available to the faculty assisting the students with the project. Funds were also transferred from the labor category to the equipment category according to the needs of the project. One of the

benefits of aligning sponsored research with thesis research is that the salary of the military officer students is not charged against the associated projects.

2. Travel

As stated before, travel was initially allocated more funds as the assumption was that students would be travelling to other universities to deliver the MC3 ground stations. After finding out that this travel would be delayed, the funds were redistributed to equipment. The travel supported for this project funded student and faculty travel to Blossom Point, MD to see the tracking facility and to talk with the CGA software engineers. Also, the students and faculty traveled to the NRL labs to see the MC3 building process. Travel funds were also used to go to the CubeSat Workshop in San Luis Obispo, CA, and the Small Satellite Conference in Logan, UT.

3. Equipment/Supplies

The equipment and supplies budget was broken down into two categories: Equipment greater than $5,000 and equipment less than $5,000. The different categories exist because those purchases greater than $5,000 do not accrue indirect costs, which will be discussed later. To date, there were only two purchases greater than $5,000: the Yagi Antennas ($10,115) and a 10 foot dish antenna ($46,766). The 10-foot dish antenna is to enable future capabilities for the MC3 project. The equipment category represented the majority of the funds spent because of the statement of work directing NPS to purchase parts and construct a MC3.

The MC3 design is intended to be relatively inexpensive to enable distribution to multiple sites, including government and university locations. The estimated total cost of one MC3 is around $100,000; however NPS did not have to purchase all the parts listed in the MC3 design as some had been procured by NRL for the NPS MC3. One of these parts was the GDP Space Systems radio which is currently almost half of the MC3 cost. The NRL purchased four of these

radios at a price of $39,200 per unit. There were other parts that were transferred to NPS from NRL, which do not figure in the total NPS equipment expenditures. Additionally, there are also a few parts that were purchased by NPS that are no longer being used in the MC3 design.

4. Contract/Services

The contract/services category of the budget was designated for the funds allocated towards paying of conference registration fees and other associated costs. The only registration fees came from the satellite conferences attended and total cost to date is $560.

5. Indirect Costs

Indirect costs are used by NPS to cover costs that are not directly covered by the project. These costs are common throughout different organizations and vary greatly. The NPS fixed rate for FY11 was 30.97%. Indirect costs are applied to labor, travel, some contracts/services, and equipment purchases less than $5,000.

B. FUTURE BUDGET COST ESTIMATION

As this is the first thesis done on MC3, and the beginning of an ongoing project here at NPS, a future budget cost estimation is applicable. The author only looked at two years into the future of the project, but also considered interns and other labor costs as well as military student costs, even though the military student costs are not charged to the MC3 budget. Professors and lab assistants also cost against the project, but portions of their salaries are paid through NPS and not the project representing value to the project.

1. Estimated Labor Cost/Value

The distinction is made between the cost of labor that is directly charged to the project and the value of labor applied to the project that is not a direct

charge to the project. For example, a military officer who chooses to work on the MC3 project will most likely spend around nine months on the project, but his labor is not billed to the project. In addition to the time spent on the project, he is also taking classes and doing other military duties, with some of the classes dedicated to thesis work starting around nine months before graduation. The estimated time working on the project for those nine months would be around ten hours per week. Ten hours per week was based on the experience of both students currently working on the project, the author and his colleague. Assuming four work weeks per month, yields a total of about 360 hours. The 2011 military pay scale for an O-3 and O-4 is used to calculate the annual value of their time, taking into account the housing allowance for Monterey and subsistence allotments that these military officers receive each month. Multiplying the hourly rate by the number of hours worked on the project gives an estimate of $39,500 for one O-3 and one O-4 naval officer working on the project for a year.

Labor for faculty and staff was calculated based on hourly rates provided by the PI. The MC3 project up to this point has involved primarily three faculty and staff members and hours worked on the project were estimated for FY10 and FY11 and projected for FY12 and FY13, producing Table 3.

Labor	FY11 (hrs/wk)	FY12 (hrs/wk)	FY13 (hrs/wk)
Military Students	7	7	7
Lab Manager	3	5	3
Software Eng	2	5	3
PI	3	4	3

Table 3. Estimated Work Hours/week on MC3 project

Using 52 weeks a year and with the salaries provided, the following total labor cost/value was produced:

Labor	Estimated Cost/Value
Military students	$118,500
Lab Manager	$28,600
Software Engineer	$33,800
PI	$41,600

Table 4. Estimated total faculty Labor Cost/Value for FY10–FY14

Although there has not been any intern labor associated with the MC3 project to date, it is a good assumption that there will be interns working on the project in the next two years. The assumption was made that there would be a civilian graduate student and an intern working on the MC3 project for the next two years for approximately 20 hours per week. Table 5 estimates the wages associated with each:

Labor	Total Hours	Estimated Cost
Graduate Student	2,080	$54,100
Intern	2,080	$33,300

Table 5. Estimated Intern Labor Cost/Value for FY212–FY14

The future labor cost/value estimates are depicted in Table 6.

Labor	Estimated Cost
Faculty	$77,000
Intern	$87,400
Military Officers	$78,900
Total	**$243,200**

Table 6. Future Total Labor Cost/Value Estimation for FY12–FY14

The total labor cost/value estimated for the build period of the project is shown in Table 7:

Labor	Estimated Cost
Faculty / Staff	$104,000
Intern	$87,400
Military Officers	$118,400
Total	**$309,700**

Table 7. Total Labor Cost/Value Estimation for FY10–FY14

2. Future Equipment Cost

The future equipment costs will depend on whether the sponsor decides to fund NPS to construct additional MC3 ground stations. If they do, it is estimated that each the equipment cost of each MC3 will be roughly $100,000. There will be an estimated two additional MC3s constructed in the following two years for a total of $200,000. Associated with this equipment cost is the indirect cost on purchases less than $5,000. The assumption is that the only pieces of equipment that would not incur an indirect cost would be the antennas and the GDP receiver. These two items account for $50,000 per MC3 so the indirect cost would be the 30.97% of the remaining $100,000 or $31,000.

3. Future Travel Costs

There will be significant travel costs incurred if NPS is tasked with delivering these MC3s to select universities and training personnel on MC3 operations. In addition, trips to the two small satellite conferences per year will need to be calculated. The universities mentioned above are located at various points around the United States so an average of $2000 (includes airfare, per diem, rental car, and hotel) per trip per person is used. NPS is already required to deliver three MC3s, and the assumption is that two more will be delivered by NPS in the following two years. The trips to the two conferences per year were estimated at $1500 per person for the trip to the Small Satellite Conference at Logan, Utah and $600 per person for the CubeSat Workshop in San Luis Obispo, California. Tables 8 and 9 break down future travel costs:

Trip Type	Number Traveling	Price/person	Total
MC3 Delivery	4	$2,000	$8,000
Logan, UT	4	$1,500	$6,000
San Luis Obispo, CA	4	$600	$2,400

Table 8. Travel Cost Breakdown

Trip Type	Cost/Trip	Quantity of Trips	Total
MC3 Delivery	$8,000	5	$40,000
Logan, UT	$6,000	2	$12,000
San Luis Obispo, CA	$2,400	2	$4,800
TOTAL			**$56,800**

Table 9. Total Future Travel Costs FY12 through FY14

4. Total Future Costs

Table 10 estimates the total estimated future costs for the next two fiscal years (FY12 and FY13):

Cost/Value Type	Cost/Value
Labor (including Military)	$243,200
Equipment	$200,000
Indirect	$31,000
Travel	$57,000
Total	**$531,200**

Table 10. Total Estimated Future Cost/Value for FY12 and FY13

The total of $535,200 includes military labor, and as stated above military personnel labor will not be charged to the MC3 project as military students are paid from a different set of funds. Additionally, NPS provides some portion of the Faculty and Staff salaries in support of student education and research.

C. EQUIPMENT ACQUISITION

The author took on the program management aspect of the thesis when NPS's Kuali Financial System (KFS) was beginning to come on line. It has become the standard operating program used to requisition equipment and keep track of program expenditures. The author had no experience with the previous system so there was no way to compare one against another. In total, the author initiated 43 purchase requisitions to date that contained over 250 pieces of equipment. In addition, the author tracked the expenses using a separate budget sheet.

1. Equipment Purchases

As stated before, the author purchased several pieces of equipment through various orders. KFS enables a person to input the equipment desired and the associated cost from the recommended vendor. Additionally, the author requested quotes for the equipment if the cost was not publically displayed. As the PI assigned the author full program management responsibility, the order then was automatically routed to the Sponsored Program Financial Analyst (SPFA) who independently verified there were sufficient funds to purchase the item. The item then went to the Approving Official who ensured that the item abided by the rules of the acquisition process. For example, there were orders made that had to be combined because they were separate orders made to the same vendor. These orders were subsequently bundled together in one order to the vendor. After the Approving Official approved the order it went to a buyer. The buyer was then responsible for purchasing the equipment specified and often looked at other vendors to determine if it can be purchased at a lower price.

2. Equipment Cost Tracking

During the first couple of months of using KFS, the author would go to the KFS Reports page to see if the part requested had been purchased. The only indicator on that page would be to see the part and the associated cost. As the author was also accounting for purchases via a separate spreadsheet he would input the equipment part and cost and when the part was received he assumed that the cost would then be final. However, there would be times when the cost in KFS would change, even after the part was received. KFS now lists two columns indicating an actual or an encumbered expense that alleviates this part of keeping an up to date balance for an account.

3. Acquisition Process Improvement

As stated before, the author had no experience with the system prior to KFS, and has now had extensive time inputting requisition orders into KFS. The author feels that there can be improvements made to the acquisition process here at NPS. The biggest concern from someone who manages a program's budget is how much money remains in the account. As stated above, KFS now has two columns for actual and encumbered expenses, but that still does not show proof of the purchase. Having an actual purchase receipt from the buyer's purchase linked to the requisition number in the KFS reports would be extremely helpful for those that keep track of their budgets.

Another feature on the KFS report that is already embedded, but not used, is the buyer column. The KFS report for the MC3 project has the buyer column listed, but no buyers assigned. The knowledge of which buyer assigned to the acquisition would be helpful on the report to ensure accountability for the purchase. To date, the only way to find out which buyer was assigned is to look up each requisition number. Another useful feature that should be incorporated into the KFS report is a status column. Currently, to find out the status one must go into the requisition log and pull up that individual order. Sometimes, there is information there from the buyer stating the purchase status, but sometimes

there is not. A status column in the actual KFS report page would be helpful to keep track of equipment purchase status. The status column could state the estimated shipping date, date purchased, and tracking number. Figure 16 is a screenshot of an equipment transaction report provided by KFS.

KFS Transaction Report - Equipment/Supplies

9/7/2011 11:20:10AM

TITLE: MOBILE CUBESAT COMMAND CONTROL (MC3)
JOB ORDER: R7DWD
FISCAL OFFICER: Newman, James H
SPONSOR:

FISCAL YEAR: 2011
KFS ACCOUNT NUMBER: 5770411
FUNDING DOCUMENT NUMBER: M448432
EXPIRATION DATE: 9/30/2012 12:00:00AM
INDIRECT RATE: 30.97

Document #	Buyer	Requester	Vendor	Actual Expense	Encumbered Expense
11KDZW901		Griffin, Robert	PROVANTAGE CORP	$871.54	$0.00
11KDZW901		Griffin, Robert	PROVANTAGE CORP	$70.75	$0.00
11KDZW902		Griffin, Robert	GSA ADVANTAGE/FSS	$3,650.00	$0.00
11KDZW903		Griffin, Robert	UNITED OFFICE SOLUTION, INC.	$333.39	$0.00
11KDZW904		Griffin, Robert	SmartVM.com	$690.00	$0.00
11KDZW904		Griffin, Robert	SmartVM.com	$28.39	$0.00
11KDZW905		Griffin, Robert	HAM RADIO OUTLET	$2,504.00	$0.00
11KDZW906		Griffin, Robert	BARCODES, INC.	$1,050.55	$0.00
11KDZW907		Griffin, Robert	GSA ADVANTAGE/FSS	$4,302.18	$0.00
11KDZW908		Griffin, Robert	Swift Systems	$2,490.00	$0.00
11KDZW909		Griffin, Robert	DR. SCOTT	$0.00	$79.98
11KDZW909		Griffin, Robert	DR. SCOTT	$0.00	$8.25
11KDZW910		Griffin, Robert	M2 Antenna Systems, Inc	$404.00	$0.00
11KDZW910		Griffin, Robert	M2 Antenna Systems, Inc	$26.58	$0.00
11KDZW911		Griffin, Robert	DIGI-KEY CORPORATION	$0.00	$175.00
11KDZW911		Griffin, Robert	DIGI-KEY CORPORATION	$0.00	$7.34
11KDZW912		Griffin, Robert	CDW-G, INC	$0.00	$578.62
11KDZW914		Griffin, Robert	INLAND ELECTRONICS	$0.00	$25.60
11KDZW914		Griffin, Robert	INLAND ELECTRONICS	$0.00	$7.64
11KDZW915		Griffin, Robert	TALLEY COMMUNICATIONS COR	$0.00	$1,215.64
11KDZW915		Griffin, Robert	TALLEY COMMUNICATIONS COR	$0.00	$54.72
11KDZW916		Griffin, Robert	DCB Unlimited	$0.00	$1,702.00
11KDZW916		Griffin, Robert	DCB Unlimited	$0.00	$212.06
11KDZW917		Griffin, Robert	ICOM AMERICA INC	$0.00	$7,732.00
11KDZW918		Griffin, Robert	UNIVERSAL RADIO, INC.	$0.00	$419.00
11KDZW918		Griffin, Robert	UNIVERSAL RADIO, INC.	$0.00	$9.99
11KDZW919		Griffin, Robert	Acopian	$0.00	$752.00

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Figure 16. Screenshot of KFS Report for MC3 Project

The acquisition process at NPS would be a great thesis topic for a business school student to review for improvements. The process, like any other government acquisition program, can be improved in order to effectively drive down costs and increase savings. One of the areas in particular that could be examined is the acquisition procurement process. There are areas within this process, especially looking at the long approval chain and the actual procurement of equipment, that can be improved. The author spent a great deal of time researching and inputting purchase requisitions including receiving price

quotes from vendors and initiating sole source documentation. The requisition requests were then submitted through the approval process and then sometimes were delayed in arrival for various reasons. At this time in the government when budgets are dwindling, efficiency and cost savings are at a premium and must be sought out whenever possible to ensure that the military continues its superiority throughout the world. NPS should always be open to ideas that incorporate greater efficiency and more cost savings.

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IV. ORBIT AND GROUND STATION ANALYSIS

To understand the capability of a network of ground stations, an analysis was needed to determine ground station coverage of satellites in representative orbits. Three orbits were considered: a 60 degree orbit with perigee at 480 km altitude and apogee at 770 km altitude, a Satellite Tool Kit (STK) defined sun-synchronous orbit with an inclination of 97 degrees and an altitude of 600 km, and the orbit of the International Space Station (ISS), at 51.6 degrees and about 400 km. The first orbit is the projected orbit of the Space-based Telescope for the Active Refinement of Ephemeris (STARE) CubeSat. STARE utilizes a Colony II bus with a telescope payload designed to observe orbital debris to provide better data for space situational awareness. The Operationally Unique Technology Satellite (OUTSat) consists of the NPS CubeSat Launcher (NPS-CuL) and eight Poly Picosatellite Orbital Deployers (P-POD). OUTSat is significant in this study because of its capacity to launch Colony II spacecraft into the orbits mentioned above. The other two orbits were determined to be likely orbits for small satellites and understanding access to ground stations from these orbits would be of benefit to users of the MC3 network. The analysis was conducted using STK software with the orbits modeled using up to J4 Perturbations.

A. SCENARIO PARAMETERS

Various scenario parameters were set to remain constant throughout the process. While some were assumed, others were calculated based off existing information from sources.

1. Satellite Lifetime

Satellite lifetime was needed before an effective analysis could be conducted as the time period to run the analysis needed to be determined. STK software uses several models to predict satellite lifetimes, but the model used in

this analysis was the NRLMSISE 2000. This model was produced by the NRL in 2000 and is valid for satellites with an altitude below 5000 km. The model inputs were drag coefficient, solar radiation pressure coefficient, drag area, area exposed to the sun, and mass of the satellite. The drag and solar radiation pressure coefficients were left at the default STK model values of 2.2 and 1.0 respectively as these are the values used for a typical spacecraft [10]. The mass of the satellite was estimated at 4 kg based off the current CubeSat standard, permitting 1.33 kg per 1U of CubeSat [11]. The drag area was calculated using the best and worst case drag scenario for a Colony II spacecraft. A Colony II spacecraft is a 3U model, signifying that it is a 10 x 10 x 30 cm structure. The scenario where there would be the least amount of drag is when the drag surface area is only 10x10 cm. The worst case scenario is when the satellite experiences the most surface area, or when the surface area is the 10x30 cm rectangle with the solar panels extended. These geometric maximimum and minimum surface areas are 0.21 meters squared and 0.01 meters squared respectively. However, for purposes of comparison to a study done by Lawrence Livermore National Laboratory (LLNL), the maximum and minimum surface areas analyzed were a minimum of .03 meters squared and a maximum of .09 meters squared[12]. The drag areas for both of these conditions were then inputted to produce a maximum and minimum lifetime. The area exposed to the sun was manipulated to determine if it had a significant contribution to the calculation, but after inputting a high and low value the results differed by only 10% so the area exposed to the sun was held constant at 0.03 meters squared. Figure 17 is a screenshot from STK used to calculate satellite lifetime.

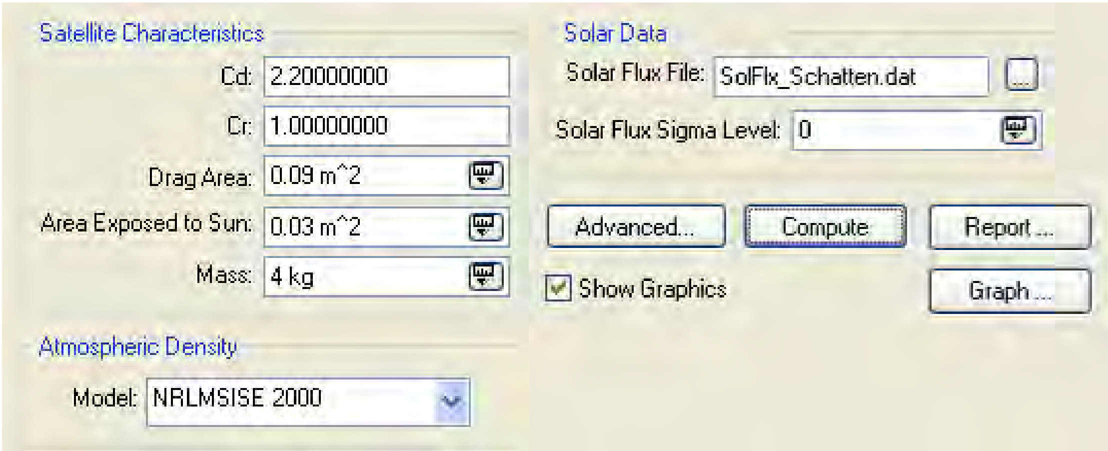

Figure 17. STK Screenshot for satellite lifetime calculation

Each satellite's orbit was used to determine the lifetime of the satellite and upon inputting the drag areas into the model, the following results were achieved:

Orbit	Max. Drag	Min. Drag
480x770 km	12.9 years	35.5 years
Sun Sync @600 km	15.5 years	45.1 years
ISS	105 days	316 days

Table 11. Estimated orbit lifetimes.

The lifetimes calculated using the model in STK roughly corresponded to similar results obtained by LLNL when researched using an orbit of 700 km. The results of their study put a 3U CubeSat as having a maximum average lifetime of 57 years and a minimum average lifetime of 22 years [11]. The orbit used in the analysis for STARE is lower than 700 km circular orbit used by LLNL and therefore one would expect the lifetime to be less. Based off the lifetime calculations a scenario timeline of one year was used. Even though a satellite in the ISS orbit will not have a lifetime of a year, data from a year will be divided into weeks and days making the analysis pertinent to the orbit.

2. General Scenario Assumptions

The ground stations used were based off the proposed locations of MC3s that NPS would deliver to universities and other projected nodes in the network. The following ground station locations were used:

- Fairbanks, Alaska (University of Alaska)
- Logan, Utah (Utah State University)
- Dayton, Ohio (Air Force Institute of Technology)
- Monterey, California (NPS)
- Albuquerque, New Mexico (AFRL)
- College Station, Texas (Texas A&M University)
- Melbourne, Florida (SGSS)
- Pearl City, Hawaii (University of Hawaii)
- Agat, Guam (Naval Base Guam)

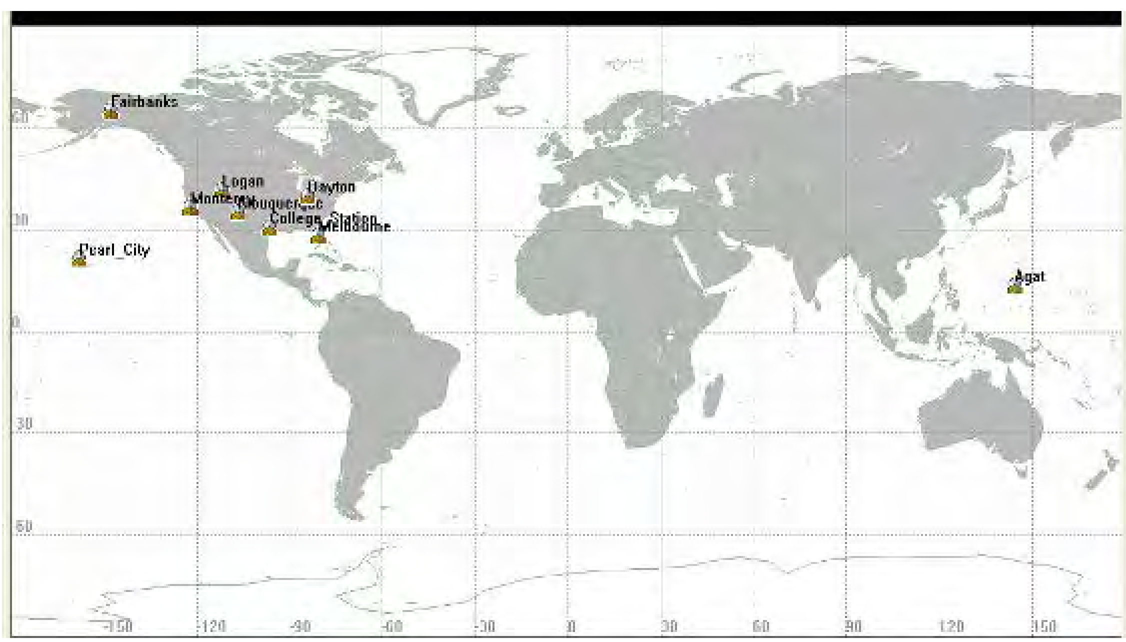

Figure 18. STK screenshot of ground station locations

Figure 18 displays the ground station locations throughout the world. Each ground station was modeled with a 10 degree elevation constraint when

communicating with the satellite signifying that an access cannot occur until the satellite is 10 degrees above the horizon from the location and the ground station terminates the access when the satellite falls below 10 degrees. An access is defined as the time the satellite is in view of the ground station. An access does not signify that there is a good communication link, nor does it signify the start of a communications link. Accesses are used throughout this analysis to demonstrate the hypothetical time a satellite is in view of the ground station with the 10 degree constraint. The reality is that a communications link with a satellite may occur at the start of the access time, at some point during the access, or may never occur during an access time. The most useful data when analyzing accesses is the average number of accesses per day, the average time per access, and the total average access time per day. This data was calculated for each orbit and displayed in tables.

3. STK Set-up

The above-mentioned orbits were entered into STK using the orbit wizard function and ground stations were entered using the city database on STK. Accesses were computed by selecting the desired object (satellite/orbit) and then associating all ground stations. STK ran the model and determined the number of accesses associated with the object to the ground stations based off initial constraints and orbital dynamics. The scenarios were run once for the time period for all three orbits.

B. 60 DEGREE 480X770 KM ORBIT

1. 20 July 2011–20 July 2012 Analysis

OUTSat on NRO L-36 is currently scheduled to launch in July, 2012 and so a one year orbit from July to July makes sense. The following data was obtained when running the year long analysis through STK for the specified orbit:

Locations	# of Accesses	Total Access Time (hours)
Fairbanks, Alaska	1840	224
Logan, Utah	1997	231
Dayton, Ohio	1784	210
Monterey, California	1596	190
Albuquerque, New Mexico	1529	211
College Station, Texas	1381	166
Melbourne, Florida	1323	159
Pearl City, Hawaii	1212	146
Agat, Guam	1140	137

Table 12. Year long analysis for 480x770 km orbit access times

While this data is interesting for total number of accesses and total access time, further refinement is needed to better portray the merits of each location. Table 13 was constructed using data from Table 12.

	Latitude of Ground Station (degrees North)	Average Number of Access/day	Average number of minutes/access	Total average access time/day
Fairbanks, Alaska	64.8	5.04	7.30	36.8 minutes
Logan, UT	41.7	5.47	6.93	37.9 minutes
Dayton, Ohio	39.6	4.89	7.07	34.6 minutes
Monterey	36.6	4.37	7.15	31.3 minutes
Albuquerque, NM	35.1	4.19	7.18	30.1 minutes
College Station, TX	30.6	3.78	7.22	27.3 minutes
Melbourne, Florida	28.1	3.62	7.23	26.2 minutes
Pearl City, Hawaii	21.4	3.32	7.22	24.0 minutes
Guam	13.3	3.12	7.20	22.5 minutes

Table 13. Access Analysis for 480x770 km orbit

The data presented indicates that Logan, Utah will have the most access opportunities to communicate with the satellite and the most average access time per day. Fairbanks, Alaska, comes in second with Dayton, Ohio, close behind. Also, the ground stations are ordered according to latitude and there appears to be a direct correlation between the latitude and access times; the higher the latitude will result in more accesses and access times. This coincides with the fact that the spacecraft has a high inclination of 60 degrees resulting in higher latitude ground stations having more accesses. However, while Guam and Hawaii have the least amount of accesses and averages they are advantageous to have due to their location and no other ground stations located nearby.

Due to the close proximity of the ground stations in the United States there exists multiple overlaps of accesses with ground stations. Figure 19 shows the swath of the STARE satellite during a pass on 20 July 2011. The swath is defined as the satellite's view during this pass and was modeled to coincide with the 10-degree elevation constraint imposed on the ground stations.

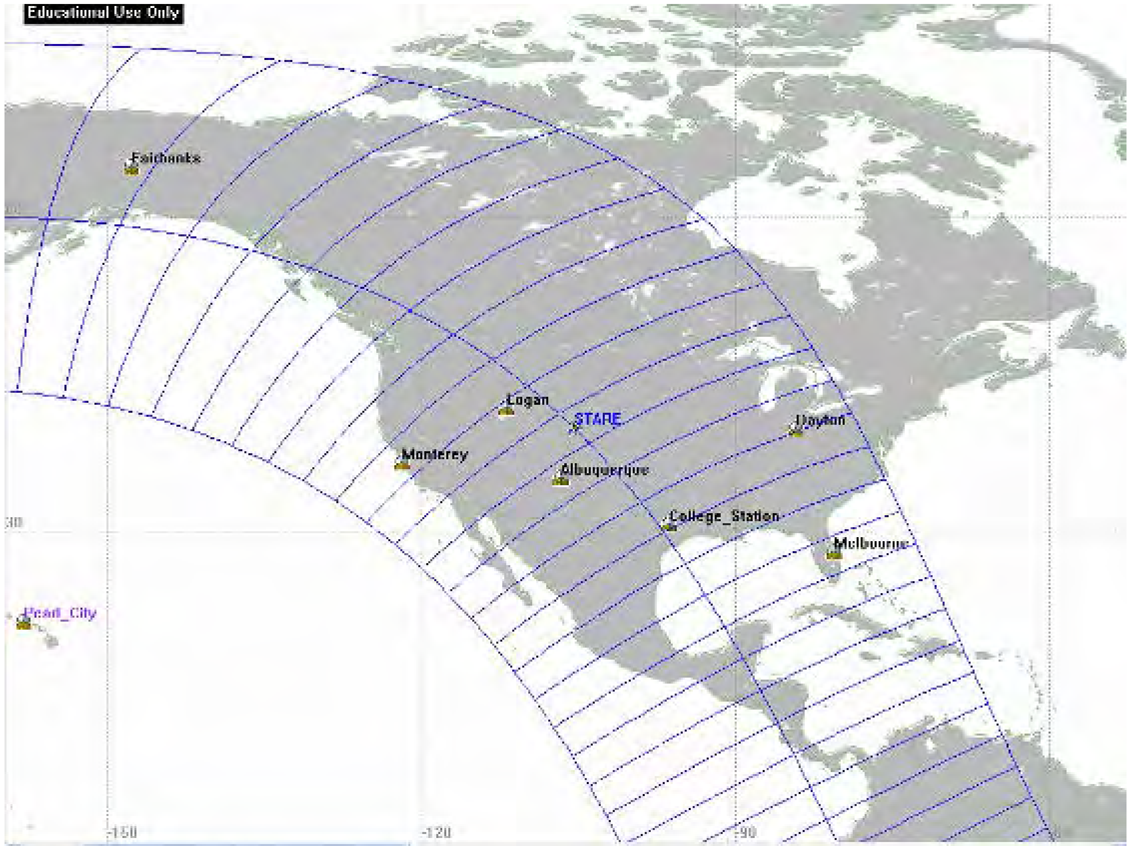

Figure 19. STARE swath and pass on 20 July 2011

During the pass with apogee in the northern hemisphere (Figure 19), the entire United States is in view of the satellite providing for multiple accesses and overlaps between ground stations. Figure 20 depicts the start and stop of access times with the individual ground stations for the pass that occurred in Figure 19.

The bars depicted in Figure 20 represent the time period for an access for that ground station and the satellite. As seen from the figures, there are multiple overlaps during this pass between ground stations allowing multiple users to download packets if a satellite is in broadcast mode. However, when a link is required between the satellite and a ground station for command uploads only one ground station can be utilized, potentially taking away access time from

another ground station. Therefore, it is advantageous to have ground stations located in remote parts of the world even though their access times are somewhat reduced.

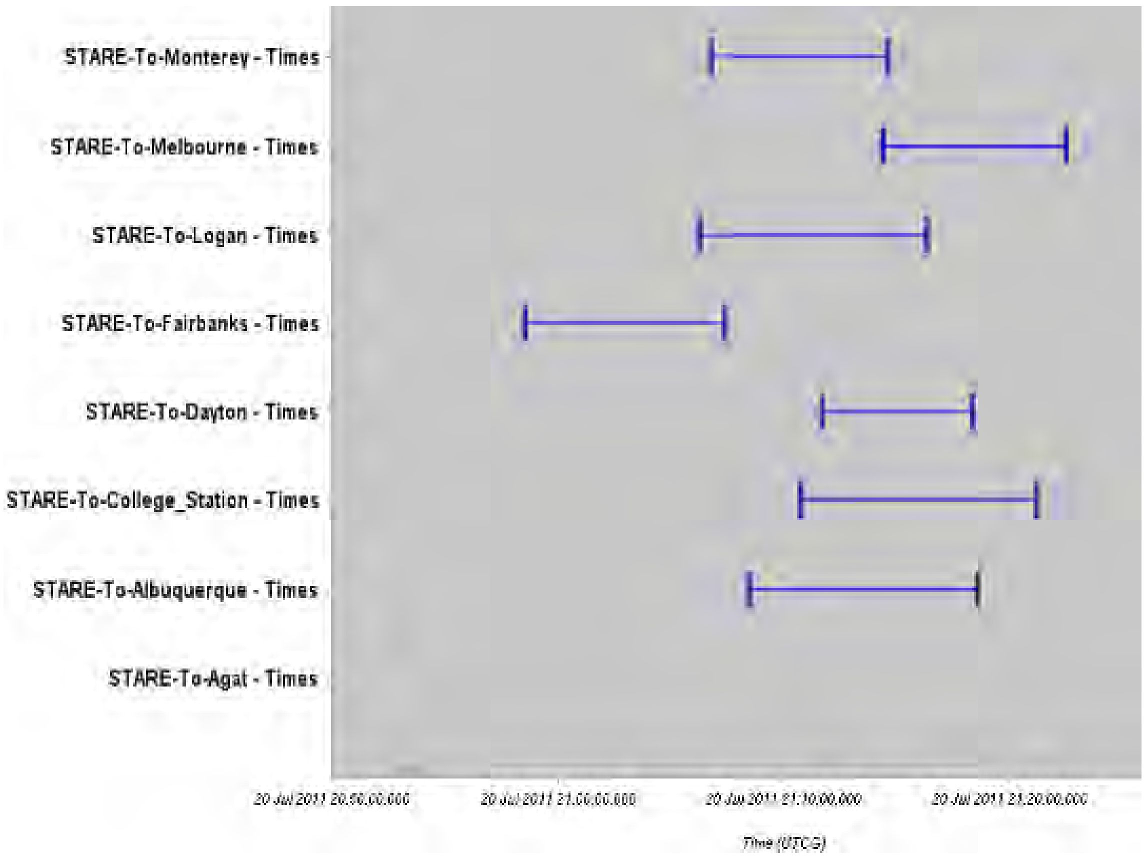

Figure 20. Satellite access on 20 July 2011

C. SUN-SYNCHRONOUS ORBIT

1. 20 July 2011–20 July 2012 Analysis

Locations	# of Accesses	Total Access Time (hours)
Fairbanks, Alaska	2864	307
Logan, Utah	1352	151
Dayton, Ohio	1310	146
Monterey, California	1246	139
Albuquerque, New Mexico	1222	136
College Station, Texas	1157	128
Melbourne, Florida	1122	125
Pearl City, Hawaii	1060	117
Agat, Guam	1011	112

Table 14. Year long analysis for Sun-Synchronous orbit access times

Table 14 lists the number of accesses and the total access times for a sun-synchronous orbit. The sun-synchronous orbit is the most advantageous orbit for access time and Table 15 further analyzes the data.

	Latitude of Ground Station (degrees North)	Average Number of Access/day	Average number of minutes/access	Total average access time/day
Fairbanks, Alaska	64.8	7.85	6.4	50 minutes
Logan, UT	41.7	3.70	6.7	25 minutes
Dayton, Ohio	39.6	3.59	6.7	24 minutes
Monterey	36.6	3.41	6.7	23 minutes
Albuquerque, NM	35.1	3.35	6.7	22 minutes
College Station, TX	30.6	3.17	6.7	21 minutes
Melbourne, Florida	28.1	3.07	6.7	21 minutes
Pearl City, Hawaii	21.4	2.90	6.6	19 minutes
Guam	13.3	2.77	6.6	18 minutes

Table 15. Access Analysis for Sun-Synchronous orbit

Analyzing this data reveals that Fairbanks, Alaska, is the best location for a ground station when utilizing a sun-synchronous orbit due to its high latitude. Once again, due to the high inclination of the orbit, 97 degrees, the highest accesses come with the highest latitude located ground stations. The swath of a satellite in this sun-synchronous orbit is shown in Figure 21.

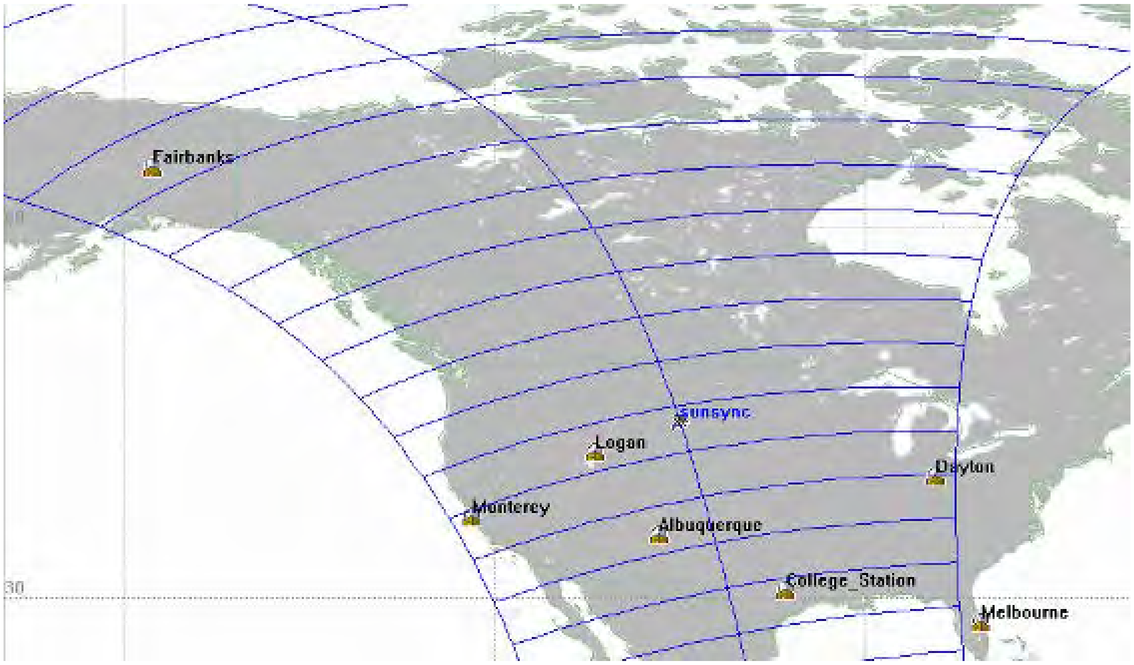

Figure 21. Sun-Synchronous satellite swath and pass on 21 July 2011

During this ascending pass on 21 July 2011, there were some overlaps in accesses between ground stations located within the United States. The access times and overlaps are depicted in the figure below:

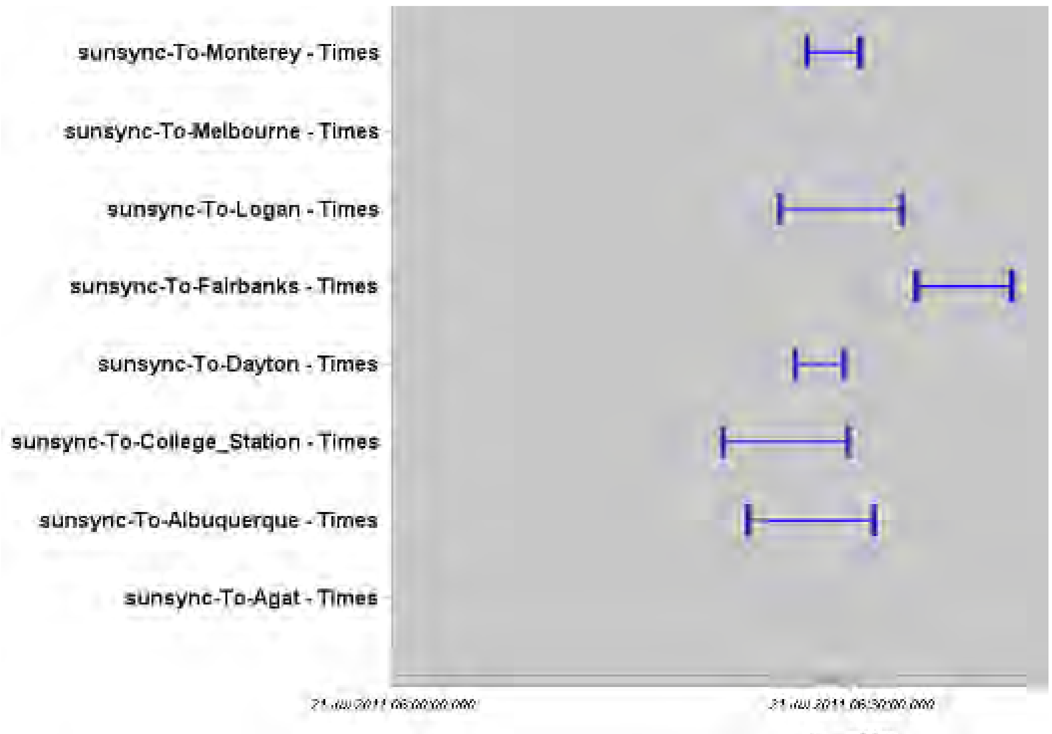

Figure 22. Satellite access on 21 July 2011

The sun-synchronous orbit, like the STARE orbit, will produce some overlaps in coverage between these ground station locations.

D. ISS ORBIT

1. 20 July 2011–20 July 2012 Analysis

Locations	**# of Accesses**	**Total Access Time (hours)**
Fairbanks, Alaska	0	0
Logan, Utah	2098	168
Dayton, Ohio	1919	144
Monterey, California	1513	119
Albuquerque, New Mexico	1407	112
College Station, Texas	1220	97.8
Melbourne, Florida	1147	92.1
Pearl City, Hawaii	1028	82.4
Agat, Guam	946	75.9

Table 16. Year long analysis for ISS orbit access times

Table 16 lists the number of accesses and total access time for an ISS orbit and Table 17 further analyzes the data.

	Latitude of Ground Station (degrees North)	Average Number of Access/day	Average number of minutes/access	Total average access time/day	
Fairbanks, Alaska	64.8	0.00	0.00	0.0	minutes
Logan, UT	41.7	5.75	4.82	27.7	minutes
Dayton, Ohio	39.6	5.26	4.50	23.6	minutes
Monterey	36.6	4.15	4.72	19.6	minutes
Albuquerque, NM	35.1	3.85	4.77	18.4	minutes
College Station, TX	30.6	3.34	4.81	16.1	minutes
Melbourne, Florida	28.1	3.14	4.82	15.1	minutes
Pearl City, Hawaii	21.4	2.82	4.81	13.5	minutes
Guam	13.3	2.59	4.82	12.5	minutes

Table 17. Access analysis for ISS orbit

In this scenario, Fairbanks, Alaska, does not have an access with ISS due to the inclination of the ISS orbit. However, excluding Fairbanks, Alaska, the trend continues with the ground stations having the highest latitude having the most accesses. The swath of a descending pass of the ISS orbit is depicted in Figure 23.

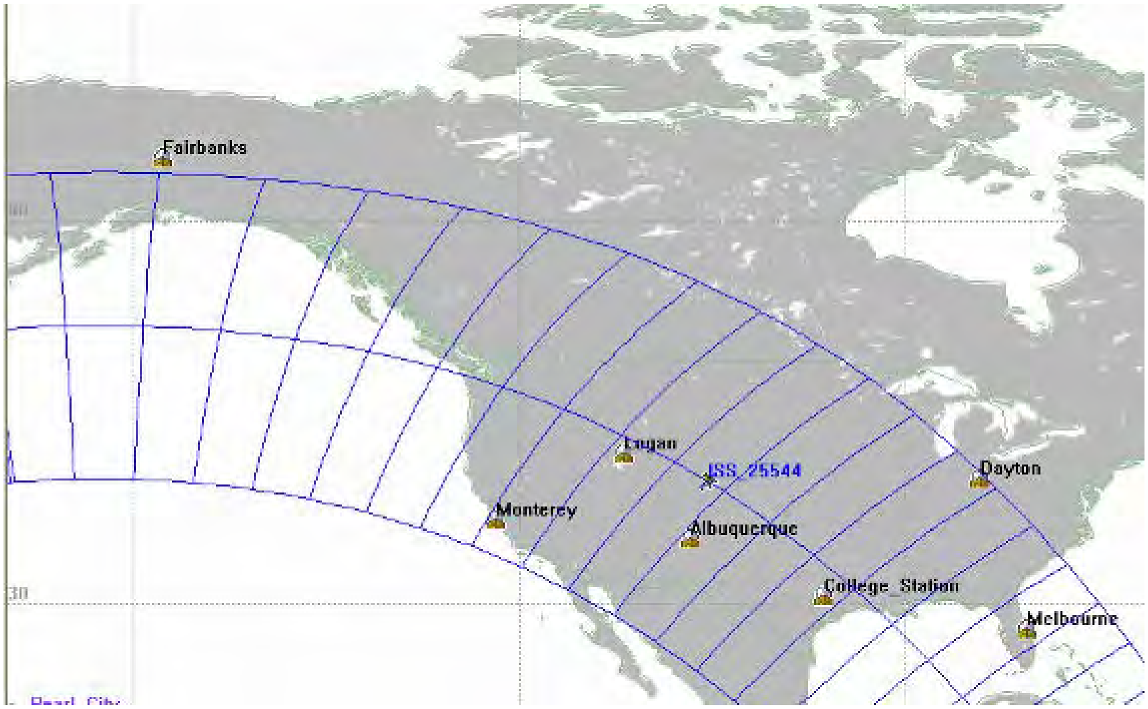

Figure 23. ISS orbit swath and pass on 21 July 2011

This pass on 21 July 2011 passes through most of the United States, but as mentioned above, the high latitude of Fairbanks, Alaska, does not result in accesses for the ISS orbit.

Figure 24. ISS orbit access for 21 July 2011

Figure 24 depicts the same pass shown in Figure 23 with the times and overlaps of accesses between ground stations.

E. ANALYSIS CONCLUSION

Ideally, before any spacecraft were launched there would be ground stations constructed at select locations around the world based on the satellite's orbit that would give the most accesses and access times. However, due to budget, country sovereignty, and the oceans one cannot place ground stations wherever is best for a satellite program. The MC3 program leverages new government programs using the Colony II Bus and educational programs at universities to benefit government experiments by placing ground stations at various locations. Although these ground stations may not always be placed in

the most strategic positions, they do allow for many accesses that the government before would not have obtained.

Trends were seen in the analysis above and the locations that were most advantageous were Logan, Utah, and Fairbanks, Alaska. These locations provided the most accesses and time per access as they were the locations with the highest latitudes. Utilizing these orbits it is advantageous to have ground stations with high latitudes. However, all locations have merit when one considers that ground stations need maintenance or become inoperable and others need to be ready to send commands and receive data. The overlaps within the United States are helpful as well if the satellite is in broadcast mode and others can compare the data packets to ensure data integrity. Overall, the proposed locations should provide many good opportunities for C2 and payload data uplink and downlink.

V. CONCLUSION

A. FUTURE WORK

1. NPS MC3

The parts for the MC3 located at NPS are all either on order or already received. The next step in the process is to install the antennas on top of Spanagel Hall at NPS and connect them to the MC3 rack. The plan for the rack as of now is to install it in an outdoor weatherized enclosure near the antennas on the roof of Spanagel Hall. The NPS MC3 will then need to be integrated with the NPS ground station room located in Bullard Hall via CGA software. Significant work with CGA software is still required to fully understand its capabilities and when NPS becomes the primary node of the network, local expertise will be critical. NRL is planning a training event on CGA to NPS in the near future, but multiple thesis topics exist across various curriculums with respect to CGA. NPS will also need to finish the frequency licensing process for the ground station.

2. MC3 Delivery

The three remaining MC3s that will be delivered to NPS by NRL are still on hold, awaiting further testing of the GDP radio. Upon successful completion of integration and testing of the MC3 with the Colony II spacecraft, NRL personnel will come to NPS and demonstrate assembly as well as provide documentation for MC3 operations. The three MC3s will then be given to selected universities; and training on operations will be provided by NPS personnel. Development of drafts of an MC3 assembly guide, an MC3 operations manual, and a CGA operations manual are still needed and should be provided by NRL.

3. Testing

Upon delivery of MC3s to other locations, a great deal of network testing is required. CGA software allows for remote access to ground stations, but testing is required to ensure that the MC3 nodes are connecting properly and capable of passing data. Simulated satellite passes will need to be demonstrated to train personnel and ensure correct operation of scheduling by the primary node at NPS. Further integration testing of the MC3 with the Colony II bus and payload need to be accomplished as well. Testing will need to be accomplished by NPS with the other university and government locations as well as with Blossom Point.

B. MC3 FUTURE ACQUISITION SUGGESTIONS

After ordering parts for the better part of the year and analyzing the cost benefits of NPS research, the author feels that the MC3 project could be improved. An important benefit of educational research done at NPS is the cost savings to the sponsor as military students are already paid through other government budgets. In addition, educational institutions typically do not cost as much as government laboratories or government contractors. MC3 is a great project whose resources could possibly have been further leveraged by giving more responsibility for the hardware development. However, if further burden is placed on universities, patience must be exercised as expertise is developed locally, extensive training and knowledge of CGA software is required. And it is important to maintain a good relationship between NRL and NPS to effectively leverage the work NRL has done in the past on these small ground stations in general and MC3 in particular.

Another important benefit of the MC3 project is the low cost of the ground station hardware. However, the biggest cost, almost 40 percent of the entire budget, is the GDP receiver. A lower cost receiver with comparable capability should be procured making the MC3 ground station even more cost effective. Lower station cost could result in more ground stations and nodes on the network providing more opportunities for data download from spacecraft.

C. SUMMARY

The MC3 program is a great educational experience that offers opportunities to not only military students at NPS pursuing masters degrees, but students at other universities wanting to enhance their knowledge of spacecraft communications. Implementing a ground station architecture before the spacecraft are launched is important to the success of the Colony II Bus program. In addition, the MC3 is an affordable design utilizing existing government owned software providing costs savings for the government and allowing for educational opportunities for students. The proposed network will allow both the government and civilian Small Satellite community to reap the benefits of increased control of their respective spacecraft and increased download of payload data. The experience and educational opportunities the MC3 project provides greatly enhance the NPS experience.

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